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This document describes progress toward development of a general capability for high resolution microwave surveillance and imaging using large, sparse, self-cohering arrays. During the last year progress has been made in the following areas: Assessment of the potential advantages of large self-cohering arrays, development of advanced system concepts (ground-based, airborne and spaced-based radio cameras), refinement of self-cohering techniques compatible with these system concepts, hardware testing of self-cohering techniques compatible with these system concepts, hardware testing of

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HIGH ANGULAR RESOLUTION MICROWAVE SENSING WITH LARGE, SPARSE, RANDOM ARRAYS

Annual Technical Report

to

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

AFOSR-78-3688

Valley Forge Research Center
The Moore School of Electrical Engineering
University of Pennsylvania
Philadelphia, Pennsylvania 19104

ABSTRACT

This document describes progress toward development of a general capability for high resolution microwave surveillance and imaging using large, sparse, self-cohering arrays. During the last year progress has been made in the following areas: Assessment of the potential advantages of large self cohering arrays, development of advanced system concepts (ground-based, airborne, and spaced-based radio cameras), refinement of self-cohering techniques compatible with these system concepts, hardware testing of self-cohering techniques, and development of methods for enhancement of image quality associated with large sparse arrays.

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HIGH ANGULAR RESOLUTION MICROWAVE SENSING WITH LARGE, SPARSE, RANDOM ARRAYS

RESEARCH OBJECTIVES

The long-term objective of this research program is the development of a general capability for high resolution microwave surveillance and imaging. Fundamental to such a general capability is the ability to cohere large, poorly surveyed possible flexing microwave arrays. Some form of adaptivity, referred to in this document as self-cohering, is required in order to form high quality beams with such arrays.

The specific objectives of the program are:

1. To expand understanding of self-cohering arrays in a broad range of applications.

2. To understand the effects of multipath and other propagation phenomena on the operation of large, self-cohering arrays; to devise system concepts for minimizing the degrading effects of such propagation irregularities.

3. To understand the effects of jamming and other interference phenomena on the operation of large, self-cohering arrays; to devise system concepts for minimizing the degrading effect of these interference phenomena.

4. To devise spatial and temporal signal processing techniques which optimize the beam characteristics of large, self-cohering arrays in the presence of noise, interference, multipath, and other degrading phenomena.

5. To design and perform experiments to test the models, system concepts, and theories developed in 1 through 4.

STATUS OF THE RESEARCH EFFORT

Prior to the initiation of AFOSR support, two techniques for self-cohering were developed which use information external to the array (beacon signals or target reflections) to aid in beamforming. Both of these self-cohering concepts have been verified experimentally (at L-band) at our Valley Forge Research Center test range.

During the first two years of support by AFOSR, program effort was focused on enhancing self-cohering capability, development of spread spectrum and nulling techniques for reducing the effects of interference on self-cohering of real and synthetic apertures, modelling the effects of multipath on self-cohered beams and experimental verification of these models, and on the development of advanced system concepts (the airborne radio camera and forward-looking synthetic aperture radar) [1], [2].

During the present year work has continued on the development of advanced system concepts (ground based, airborne, and space based radio cameras), on refinement of our self-cohering techniques compatible with those system concepts, on hardware testing of self-cohering techniques, and on the development of methods for enhancing the quality of microwave images obtained through large, sparse arrays. The present focus of the research effort is directed primarily toward image quality improvement in very sparse, random microwave imaging systems, and toward a study of the feasibility of large, sparse, random apertures using multiple vehicles.

Advantages of Large Self-Cohering Arrays

For a number of years the Valley Forge Research Center has been developing an understanding of the applicability and advantages of large self-cohering arrays for a broad range of applications. This extended study, much of it supported by AFOSR, has discovered the following potential advantages associated with those arrays:

1. Improvement in the range/power trade off in radar and communications as a result of the high power-aperture product (owing to large size).
2. Improvement in resolution and tracking (or pointing) accuracy owing to the small beamwidth associated with large arrays.
3. Lowered probability of intercept and improved interference rejection in communications, direction finding, and radar owing to the small beamwidth associated with large arrays, and owing to the high degree of null control associated with individual-element phase control. Adaptively placed nulls can track moving interferers and ease sidelobe level requirements.

4. Extension of the capability for high resolution searching and imaging in either monostatic or bistatic operation. The technology for self cohering of large arrays complements the imaging capability of conventional synthetic aperture radar (SAR) in two ways:

   a. It loosens the restrictions associated with conventional SAR; specifically, it provides for:

      i. Variable, loose-tolerance flight paths by means of adaptive signal processing.

      ii. Reduced data rate through aperiodic data thinning.

      iii. Reduced effects of propagation anomolies through use of adaptive signal processing.

      iv. Improved RFI suppression through adaptive signal processing.

   b. It provides a real-aperture alternative to SAR for high-resolution imaging.

      i. No platform motion is required.

      ii. Arbitrary array configuration is permitted owing to individual-element phase control.

      iii. Tolerances are looser than conventional because of the adaptive signal processing.

      iv. Aperiodic or random thinning of large arrays provides greater frugality than conventional large filled arrays.

      v. Scanning is by sector (angle) as in conventional radar, rather than strip mapping as in conventional SAR.

Ground Based Radic Camera

[3], [4], and [5] begin the development of the design of a ground based radio camera. They describe a design philosophy for development of a 1,024 element two-dimensional array spread over approximately a 300 meter square. The array is divided into 32 clusters in order to achieve significant sharing of processors and associated reductions in cost. The system would be designed to operate over a 20° sector in horizontal and vertical planes which would intercept the approach flight pattern normally used by aircraft going into Philadelphia National Airport. The system would be able to image an entire 50 meter aircraft at a 10 kilometer range.

Airborne Radio Camera

A study of the potential value of distributing a microwave antenna throughout the airframe of an aircraft has shown that the increased antenna aperture can enormously increase the power-aperture product [6]. Consequently, an aircraft-size aperture will permit significantly increased detection range or, alternatively, a reduction in transmitter power at conventional range, thereby lowering the probability of intercept. Other potential values of the distributed airborne array concept result from the significantly reduced beamwidth associated with the large aperture. Specifically, the angular resolution is improved and jammer suppression is more effective in directions near the direction of the target.

A critical problem with the airborne array lies in the synchronization of the flexing aperture. Several approaches to synchronization of an airborne flexing array have been developed. These techniques use doppler filters and range gates to isolate radar returns from relatively small ground or sea clutter patches. The returns are treated as beacon signals. The simplest technique, described in [7], permits "telephoto" imaging in the direction toward the designated clutter patch. This technique was successfully tested experimentally using airborne radar data obtained from the Naval Research Laboratory. The technique will fail, however, for an aircraft which flies over water at high sea states. A doctoral dissertation has been completed on the topic of array synchronization with perturbed sea clutter [8].

A second general approach to synchronization of an airborne array, denoted "self-survey", uses the returns from several clutter patches to track the array element positions, thereby permitting normal array operation over a surveillance sector [9], [10], and [11].

Space-Based Large Array Radar

Because of the success of the designs for the airborne radio camera, some preliminary concept work has been done on application of these techniques to space radar. One concept has been developed in which a huge (100 kilometer) geosynchronous-altitude phased array is created from radar receivers, each on a separate vehicle. The transmitter is in a low orbiting space vehicle. The system is bistatic. The "cloud" of receivers self-synchronize on the back radiation from the low orbiting transmitter, the dish of which is pointing toward the ground. Data links from receivers to the ground station permit the ground facility to organize multiple receive beams that follow the transmitter. A cross-range resolution of 10 to 100 meters should be achievable on the earth's surface with such a system. A proposal is in preparation for submission to Rome Air Development Center concerning exploration of this system.[12].

Self-cohering Techniques

A doctoral dissertation has been completed on the subject of self-cohering of a large, sparse, conformal, random array by a generalized self-survey technique [11]. The technique uses beacons (or isolated clutter patches as described under "Airborne Radio Camera" above). The technique determines the positions of the unknown (or moving) antenna element locations and the unknown beacon locations. The self-survey process solves a set of multivariable nonlinear equations. These equations are shown to have several degrees of freedom. An appropriate set of "baseline" variables are defined and measured separately from the self-survey process in order that the computing algorithm produce a unique solution. Numerous computations with the computing algorithm consistently demonstrate good convergence properties. A tolerance analysis shows that the solution produced by the algorithm is relatively insensitive to errors. A paper entitled "A Generalized Self-survey Technique for Self-cohering of a Large Array" is in preparation for submission to IEEE Transactions on Antennas and Propagation.

Extension of the self-survey concept to synthetic aperture systems has been under investigation. Algorithms have been developed for both monostatic (moving transmitter/receiver) and bistatic (fixed transmitter position, moving receiver) cases. It has been determined that the equations for the bistatic case are essentially the same as those for the real aperture system described above. The properties of the monostatic equations will be described in the forthcoming Valley Forge Reseach Center Quarterly Progress Report.

Work has been completed on using radar returns from sea clutter to phase synchronize an airborne flexing array. Unlike ground clutter, the internal motion of the scatterers on the sea surface prevents self-cohering of the array by the basic radio camera algorithm. The new technique uses a self-adaptive subsystem to establish the weights on the antenna elements which produce the antenna pattern with the narrowest beamwidth. A doctoral dissertation has been completed on this subject [8], [illegible].

Certain fundamental limits upon the imaging quality of the radio camera relate to the physical characteristics of the phase synchronizing source used for adaptive beamforming. This subject has been studied in a paper, "Properties of Phase Synchronizing Sources for a Radio Camera," which has been accepted by the IEEE Transactions on Antennas and Propagation.

Hardware Testing of Self-cohering Techniques

In previous years an extensive data base has been built up using a movable, single-element, x-band transmit-receive radar designed for synthetic aperture self-cohered imaging [14]. This data permitted one-dimensional angle scan at fixed range. During the past year, the algorithms have been extended to produce range-angle images. To date, one two-dimensional image of a portion of the town of Phoenixville, Pennsylvania, at a range of 6 to 7 kilometers from our field site, has been obtained [15]. A single time-shared receiver was moved along a 40 meter cable slung between two towers 10 meters high. During the traverse, which took two minutes, the radar transmitter was pulsed at random intervals and the echo sequence was received by the cable-borne receiver. The

received signals were coherently demodulated and processed to produce an image which shows street patterns and individual houses in the town. This work was partially supported by the U. S. Army under contract DAAK-20-80-C-0250. A paper entitled "Adaptive Microwave Holograph ." was presented on this work by B. D. Steinberg at the International Optical Conference, Graz, Austria, September, 1981.

A tape of airborne radar test data was obtained from the Naval Research Laboratory. This data has been used to experimentally test the radio camera algorithm described in [7]. The experiment demonstrated that the technique works very well for synchronizing arrays using radar returns from land-clutter cells [16].

Spatial Spectral Analysis For Emitter Location*

One of the principle problems encountered with modern spatial spectrum estimation is that totally coherent arrivals from different directions, as would be encountered in fixed multipath channels, confuse the estimation method. This is true of the maximum likelihood, maximum entropy, and minimum distance methods. Approaches to overcome this difficulty have been a subject of study under this program. In particular, we have examined an extension to the maximum likelihood method which uses two directional constraints corresponding to the assumed presence of two arriving signals. The rationale for this approach is that by bi-directional pointing in the correct directions the mechanism for rejection of the unwanted signal sees no part of the signal being measured. An expression for the array output utilizing a double directional constraint had been obtained in connection with another study, though not with the idea of accommodating correlated inputs. To address correlated inputs, further modifications of the result were made and computations were carried out to establish the validity of the method. The method involves, however, a multidimensional search. (For two arrivals a three dimensional search is needed -- two in angle of arrival and one in phase difference between arrivals.) We are now examining techniques for simplifying the search and methods of determining the number of arrivals. Details of this work appear in [17].

* This work was supported in part by U. S. Army Contract DAAK-20-79-0524.

Array Processing Techniques for Communication*

The maximum likelihood method of spatial spectrum estimation has an advantage over other methods in that the array output is the true signal to which the array is pointing plus a suppressed noise and interference residue. It is for this reason used in communication. Two alternatives are known, one in which the desired signal is chosen by inputing the known direction from which the signal arrives, the other one in which known structure of the desired signal is used to generate the pointing angle. In many instances the direction of arrival is imperfectly known and the available signal structure information can be used as a supplement to aid in pointing. In connection with a study for RADC, two methods were conceived for using both approximate direction of arrival and approximate signal structure [18]. Further work on one of these methods, which we have called the "Hybrid Array", was carried out as part of the AFOSR study. We have performed analysis and computer studies using simulated signal and interference inputs. The results are very promising, suggesting that this method deserves thorough exploration. The results to date will be prepared for the next quarterly report of the Valley Forge Research Center and a paper for publication on the "Analysis and Simulation of the Hybrid Array" will be prepared simultaneously.

Image Quality Enhancement in Large Aperture Systems

Design procedures for self-cohering of a large, sparse, random, nonrigid array are now reasonably well developed, and two-dimensional microwave images are now being obtained by such an array. Distortion in measured wavefront samples (amplitude and phase) taken at the array elements caused distortions in the images processed from the samples. The phase errors are of particular concern because the image information is carried primarily in the phase. Phase errors can arise in large arrays, in particular, because the transmission medium may not be sufficiently homogeneous across a large array, and because the element position may not be known sufficiently well to permit accurate scanning of the beam. Self-cohering processes can compensate, to a great degree, for one or both of these phase error mechanisms. However, in practice the compensation

*This work was supported in part by a subcontract with Interspec, Inc., under RADC contract F30602-80-C-0230.

cannot be perfect. Furthermore, even with perfect self-cohering the phase compensation would be exact only for certain beam pointing directions (those in the directions of the beacon signals). Therefore, our research has begun to focus on techniques for maximizing the quality of the images obtained via a self-cohered array.

The radiation pattern of an array that self-coheres on a beam forming source approximates a filter which is spatially matched to that source. Thus, if the source is not a point source, or if there is multipath and scattering of the radiation from the source, the radiation pattern of the array can have its main lobe broadened and its sidelobes raised. The physical and electrical requirements that must be imposed upon sources and targets so they can be acceptable beamforming sources are described in [19].

A second source of degradation of image quality arises from the high and random sidelobe pattern of a highly thinned random array. A study is almost completed on the value of element position diversity in reducing the peak sidelobes of such an array [20], [21], [22], [24]. The use of wide-band waveforms and/or frequency diversity to reduce the peak sidelobes is also under study.*

Experimental work with the Valley Forge Radio Camera disclosed peculiar asymmetrical properties in the two-dimensional diffraction pattern of a random array. A theoretical study disclosed that the asymmetries in the diffraction pattern were due entirely to asymmetries in the distribution of the locations of the antenna elements. This work was published in [23].*

Investigation has begun on techniques for measuring directly the quality of a microwave image and using that measure to correct the beamforming and scanning process that formed that image, thereby maximizing image quality. Initial results of this study will be reported in the next Valley Forge Research Center Quarterly Progress Report.

*This work is partially supported by the Office of Naval Research under Contract No. N00014-79-C-0505.

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INTERACTIONS

Technical Presentations

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